

## An Electronically Tunable, First-Order Fabry-Perot Infrared Filter

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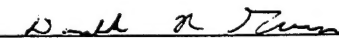
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## 1. Introduction

Our remote sensing projects in the longwave infrared (8–12  $\mu\text{m}$  band) frequently require bandpass filters that overlap molecular absorption/emission bands. Because custom filters are relatively expensive (\$5–15K), we depend on finding an appropriate filter from manufacturer's surplus stock. Frequently, the filters we obtain are not optimally matched to the desired molecular band. We have also used circularly variable, wavelength-tunable filters, but they have narrow rectangular slits ( $<1$  mm) that place significant constraints on the optical systems in which they can be used. We have developed an electronically tunable filter that can replace sets of fixed wavelength filters or be continuously scanned. In addition, its ability to rapidly change the transmitted wavelength offers a new capability for rapid wavelength-modulated detection or spectral dithering.

The filter is a scanning Fabry–Perot Interferometer (FPI) operated in first order. Although first-order (and low-order) FPIs are the basis for fixed-wavelength interference filters, and high-order ( $n > 100$ ) scanning FPIs are commercially available, we are unaware of any reports of a scanning first-order FPI.<sup>1</sup>

For collimated, normally incident input radiation, the transmission peaks of an FPI occur when the cavity spacing between the two mirrors,  $\ell$ , is an integral number,  $n$ , of half wavelengths,  $\lambda$ .<sup>2</sup>

$$\ell = \frac{n\lambda}{2} \quad (1)$$

For a first-order FPI, the cavity length is simply one-half the desired wavelength. Therefore, to tune the FPI transmission peak from 8–12  $\mu\text{m}$ , the cavity spacing must be scanned from 4–6  $\mu\text{m}$ .

We need to be concerned about other order peaks falling in the 8–12  $\mu\text{m}$  tuning range. The wavelength of any other order,  $\lambda_n$ , can be calculated for a given  $\ell$  by rearranging Eq. (1).

$$\lambda_n = \frac{2\ell}{n} \quad (2)$$

Equation (2) shows that as the cavity length scans 4–6  $\mu\text{m}$ , the second-order peak will scan from 4–6  $\mu\text{m}$ . This is well outside our 8–12  $\mu\text{m}$  tuning range and can be efficiently eliminated with an 8–12  $\mu\text{m}$  bandpass filter in the optical system. Orders higher than  $n = 2$  correspond to even shorter wavelengths and are also eliminated by the 8–12  $\mu\text{m}$  filter. In general, the region over which a first-order FPI can be tuned without overlapping another order is just one-half the longest wavelength in the desired tuning range. In our case, the maximum wavelength is 12  $\mu\text{m}$ , and the tuning range is 6  $\mu\text{m}$  (from 12–6  $\mu\text{m}$ ).

## 2. Reflective Coatings

The full-width at half-height (the bandwidth) of the FPI's transmission peak depends on the reflectance of the partially reflecting mirrors ( $R$ ), and the FPI order ( $n$ ). Higher reflectance and higher order decrease the bandwidth. The bandwidth, in percent of the center wavelength,  $\Delta\lambda/\lambda$  (%), is given by Eq. (3).

$$\frac{\Delta\lambda}{\lambda} (\%) = \frac{100}{nN_R} \quad (3)$$

$N_R$  is the reflective finesse, which is proportional to the reflectance and is given by Eq. (4).

$$N_R = \frac{\pi\sqrt{R}}{1 - R} \quad (4)$$

The bandwidth is a strongly dependent function of the reflectance. For instance, a reflectance of 0.90 corresponds to a bandwidth of 3.3%. If the reflectance drops 5% to 0.85, the bandwidth increases to 5.2% (a 58% increase). Since most mirrors will have some variation in reflectance across the tuning range, there will be a corresponding variation in bandwidth across the tuning range.

Because of their simplicity, we first investigated metallic thin-film mirrors. A partially transmitting mirror was made by coating 115 Å of gold on a ZnSe substrate. The measured reflectance and transmittance of the gold-coated surface were 0.89 and 0.012, respectively, at 10.0  $\mu$ . The reflectance was measured with a reflectance accessory in an FTIR relative to a freshly coated gold mirror. Therefore, the loss due to absorption (or scattering) was 0.098.

A low-order FPI was assembled from two of the gold-coated mirrors. The measured transmittance of the FPI at 10.0  $\mu$ m was very low, 0.01. The expected FPI transmission can be calculated from Eq. (5), where  $T_m$  is the transmission of the mirror and  $\tau$  is the transmittance of the FPI.<sup>3</sup>

$$\tau = \frac{T_m^2}{(1 - R)^2} \quad (5)$$

Based on the measured mirror transmittance and reflectance, the calculated FPI transmission is 0.015, in reasonable agreement with the 0.01 measured value. Although partially reflecting gold mirrors are broadband and inexpensive, their absorptance severely reduces the FPI throughput.

Multilayer dielectric reflectors with high reflectance and low absorption were investigated. They consist of alternating layers of high and low index material.<sup>4</sup> Each layer is one-quarter of a wavelength thick. The light reflected from successive boundaries is in phase and recombines construc-

tively. A high/low index pair is called a quarter-wave stack, and the thickness is one-quarter of the design wavelength.

A quarter-wave stack is also reflective at wavelengths near the design wavelength. The width of the reflective region around the design wavelength increases nonlinearly with the ratio of the refractive indices of the two materials.<sup>4</sup> In order to maximize the width of the reflective region, we chose Ge( $n = 4.1$ ) as the high index material. Both ZnS( $n = 2.15$ ) and ThF<sub>4</sub>( $n = 1.35$ ) were candidates for the low index material.

The phase change of the reflected wave in a quarter-wave stack is  $180^\circ$  at the design wavelength. At other wavelengths, the phase change varies from  $180^\circ$ . This has several significant effects on the performance of the FPI, which will be described below. Our coating design sought to minimize this wavelength-dependent phase by keeping the number of quarter-wave stacks as low as possible.

With these initial conditions, we selected the following design:

$$\text{ZnSe substrate/Ge/Ge/ZnS/Ge/ZnS/Ge,} \quad (6)$$

where the optical thickness of each layer was one-quarter of the  $10.0\text{-}\mu$  design wavelength. The two Ge layers adjacent to the substrate are referred to as "absentee layers" since they have very little effect on the reflectance at the design wavelength. However, they do increase the width of the reflective region.<sup>4</sup>

The calculated reflectance of the multilayer stack in Eq. (6) is shown in Fig. 1. The reflectance was calculated with a commercial program that used the matrix method from Reference 4. In the  $8\text{--}13\text{ }\mu\text{m}$  region, there are two maxima: at  $8.8\text{ }\mu$ ,  $R = 0.887$  and at  $11.6\text{ }\mu$ ,  $R = 0.893$ . At  $10.0\text{ }\mu$ , the design wavelength,  $R = 0.870$ .

The reflectance data in Fig 1 can be used with Eq. (3) to calculate the FPI's bandwidths. At the reflectance maximum ( $R = 0.893$ ), the bandwidth is 3.60%. The reflectance changes most rapidly with wavelength on the short-wavelength side of the reflective region. At  $8.2\text{ }\mu$ ,  $R = 0.855$ , and the bandwidth would be 4.98%. On the long-wavelength side,  $R = 0.858$  at  $13.0\text{ }\mu$ , corresponding to a bandwidth of 4.88%. Therefore, over the  $8.2\text{--}13.0\text{ }\mu$  wavelength range, the bandwidth varies by a factor of 1.4 (maximum/minimum).

The reflectance of a mirror fabricated to design specifications in Eq. (6) is also shown in Fig. 1. The reflectance was measured in an FTIR ( $2\text{ cm}^{-1}$  resolution) with a reflectance accessory relative to a gold-coated mirror ( $R = 0.99$ ). The reflectance is in good agreement with the calculated value at  $10\text{ }\mu$ . At both longer and shorter wavelengths, the reflectance is several percent below the calculated value. The deviation from the calculated reflectance is 0.039 at  $8.2\text{ }\mu$  and 0.011 at  $13.0\text{ }\mu$ .

The deviations in the reflectance from the design values is probably due to small variations in the Ge coating thickness. The coating vendor monitored the Ge coating thickness by measuring the transmission at  $\lambda \approx 1.0\text{ }\mu$  through a microscope slide adjacent to the mirror substrate. The absorption of

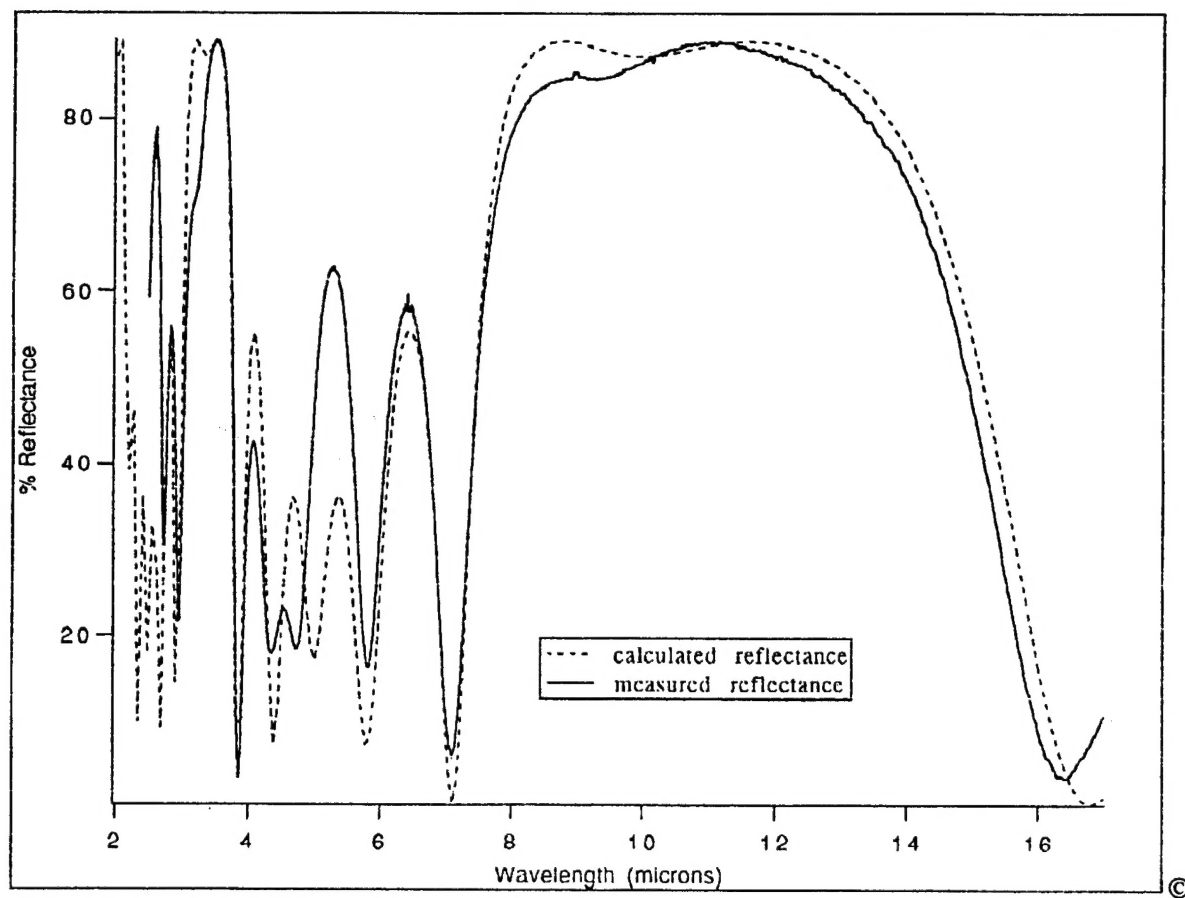


Figure 1. Measured and calculated reflectance for the coating: substrate GeGeZnSGeZnSGe.

Ge at 1  $\mu\text{m}$  is sufficiently strong that several microscope slides were required for each Ge layer. This process probably increased the error in measuring the Ge layer thickness. Shifting the optical monitoring wavelength to longer wavelengths ( $> 2 \mu$ ) should eliminate this problem.



### 3. The Fabry-Perot Interferometer

A tunable, first-order FPI was assembled using a Burleigh Instruments TL-38IR piezoelectric drive unit. The TL-38IR can scan up to  $7\text{ }\mu\text{m}$  using the RC-44 ramp generator (0–1000 V). A special jig was constructed to align the mirrors and adjust their spacing. The transmitted interferogram produced by a  $1.3\text{ }\mu\text{m}$  diode-pumped YAG laser was monitored while the mirrors were epoxied in place. A PbS vidicon camera was used to image the transmitted beam. The absorption by the Ge significantly attenuated the transmitted beam. The etalon was assembled in a clean hood to minimize the effects of contamination. Several attempts were required to obtain the first-order spacing ( $5\text{ }\mu$ ).

The mirror substrates were 1.5-in.-diameter, 1-cm-thick ZeSe. The substrates were polished to  $\lambda/20$  ( $\lambda = 0.63\text{ }\mu$ ) on the mirror side and  $\lambda/10$  on the back side. They were wedged  $0.5^\circ$ . At  $8\text{ }\mu\text{m}$ , the front surfaces are flat to  $\lambda/250$ . Assuming the deviation from flatness is spherical, the flatness finesse is approximately 125 (uncoated). This is sufficient to maintain the reflective finesse (about 30). The backside of the mirrors were also coated with a broadband antireflective coating.

#### 4. FPI Transmission Spectra

Figure 2 shows the transmission of the FPI at four different spacings. When the transmitted peak is at 8.5  $\mu\text{m}$  and 9.9  $\mu\text{m}$ , the transmission is about 80%. At 11  $\mu\text{m}$ , the transmission starts to decrease, and at 12.1  $\mu\text{m}$ , it is 50%.

The acceptance angle of the FPI is sufficiently large that the  $f/4.5$  conical FTIR beam should have only a small effect on the transmission spectrum. To maintain the bandwidth to within 10%, the maximum angle of incidence,  $\alpha$ , for the FPI depends on both the order and the reflective finesse as given in Eq. (7).<sup>3</sup>

$$\alpha \text{ (radians)} = \frac{1}{\sqrt{nN_R}} \quad (7)$$

For  $N_R = 30$  and  $n = 1$ ,  $\alpha$  is  $10.5^\circ$ , which is more than adequate to accept the  $6.4^\circ$  maximum angle of incidence in the  $f/4.5$  FTIR beam.

The wavelength dependence of the transmission maxima in Fig. 2 suggests absorption by something with increasing absorption in the 11–12.5  $\mu\text{m}$  region. We have reviewed the absorption spectra of materials that could contribute to the transmission loss.  $\text{GeO}_2$  has strong absorption centered at 11.6  $\mu\text{m}$ , and it is sufficiently broad to account for the loss out to 13  $\mu\text{m}$ .<sup>5</sup> The  $\text{GeO}_2$  could be produced by oxidation of the outer Ge layer of the FPI mirror. We can calculate the effect of absorption on the FPI transmission using Eq. (5) and equating the mirror transmission,  $T_m$ , with  $1-R-A$ , where  $A$  is the loss due to absorption (or scattering). For a typical reflectance of 0.87, absorption losses of 1, 2, 3, and 4% yield FPI transmissions of 0.85, 0.72, 0.59, and 0.48. Thus, a few percent absorption can account for the FPI transmission losses.

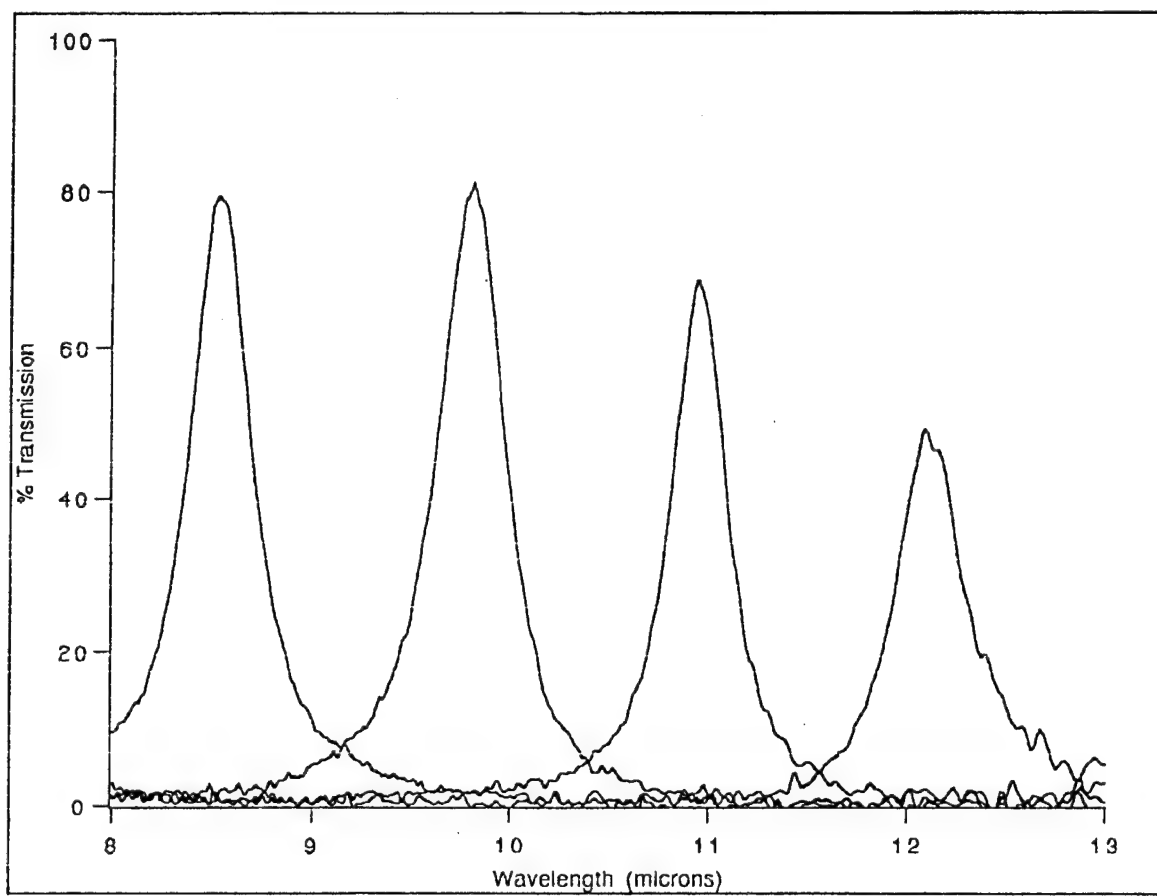


Figure 2. The FPI transmission at four different cavity spacings.

## 5. Peak Wavelength and FPI Spacing

In Fig. 3, the wavelength of the transmission peak,  $\lambda_{\text{peak}}$ , is plotted versus the FPI spacing. The solid black line in Fig. 3 has a slope of 2, which is the expected value for a first-order FPI [see Eq. (1)]. The difference between the expected and measured slopes is due to a wavelength-dependent reflective phase change in the multilayer dielectric coating.

The phase of the reflected wave from the multilayer dielectric mirror is  $180^\circ$  at the design wavelength ( $10.0\ \mu\text{m}$ ). This is the phase change used to derive Eq. (1), which predicts that the FPI mirror spacing should be one-half the wavelength. In Fig. 3, we can see that the peak wavelength at  $10\ \mu\text{m}$  occurs at a  $5\text{-}\mu\text{m}$  spacing (to within a few tenths of a micron). However, at wavelengths shorter than  $10\ \mu\text{m}$ , the spacing is smaller than expected, and at wavelengths larger than  $10\ \mu\text{m}$ , the spacing is larger than expected. To scan the wavelength from  $8$  to  $12\ \mu\text{m}$  now requires scanning the spacing from  $3.3$  to  $6.3\ \mu\text{m}$ ; about one micron more than expected for a mirror with no wavelength-dependent phase change.

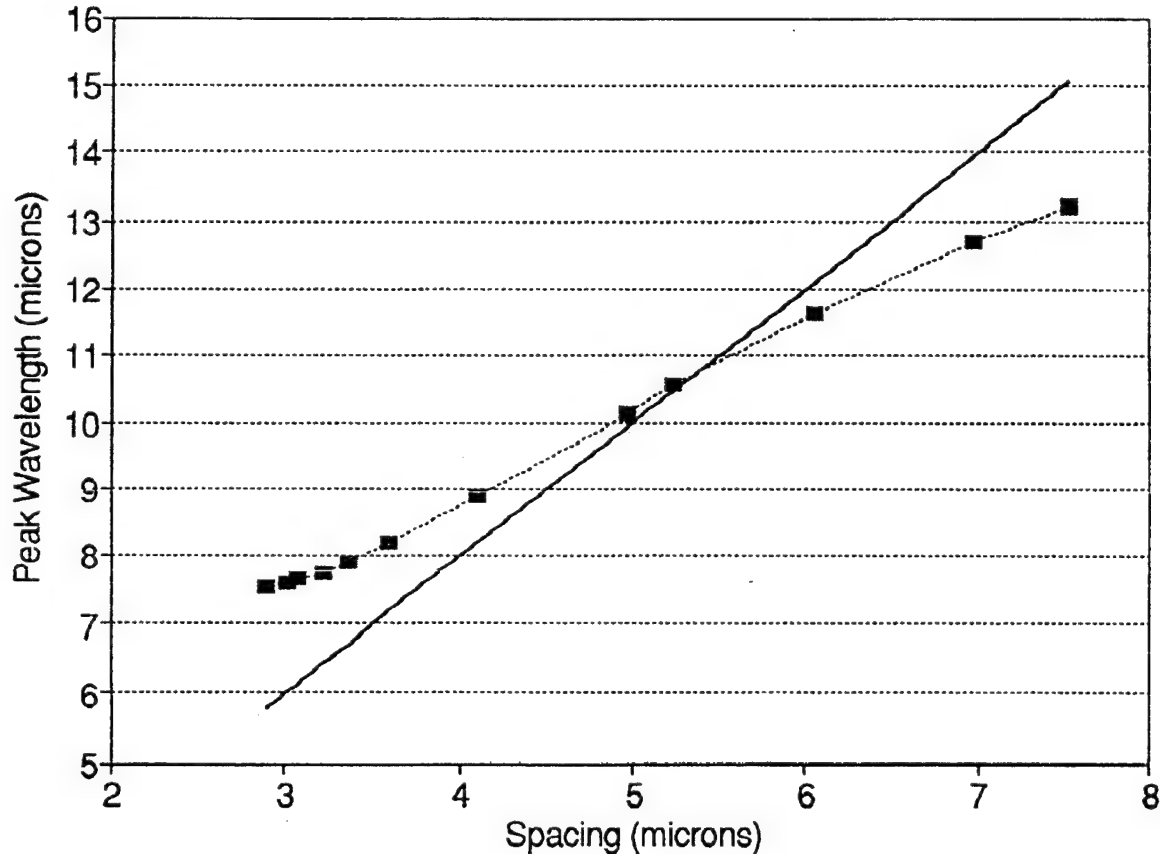


Figure 3. The measured FPI peak wavelength as a function of cavity spacing. The solid line is from Eq. (1) and has a slope of 2.0.

The data in Fig. 3 were taken with a spectral mirror set in which a stripe of the substrate was masked during the mirror coating process. At each FPI spacing, spectra were recorded of both the coated and uncoated portions of the mirror. The uncoated FPI spacing was calculated from the uncoated free spectral range (there is no wavelength-dependent phase change for the uncoated mirror). The spacing in the coated portion of the FPI is just the coated spacing minus twice the coating thickness.

The coating thickness was measured using a Sloan Dektak surface profiler. The thickness was measured at seven locations, and the average thickness was  $3.71 \pm 0.44 \mu\text{m}$  ( $1 \sigma$ ). This is significantly smaller than the  $4.82 \mu\text{m}$  calculated from the coating design using the indices of refraction for Ge and ZnS given earlier. The Dektak profiles showed the coated surface to be rough compared to the uncoated substrate. Surface bumps of  $1\text{--}1.5 \mu\text{m}$  occurred frequently, and the average roughness (peak-to-peak) was approximately  $0.5 \mu\text{m}$ . The surface roughness contributes significantly to the error in measuring the coating thickness. In addition, the coating vendors previously described difficulty in producing the Ge layers, which may cause the actual coating thickness to differ from the calculated value. A third value for the coating thickness can be calculated by recalling that the reflected phase should be  $180^\circ$  at the design wavelength. This is equivalent to assuming that the cavity spacing is  $5 \mu\text{m}$  when the transmitted peak wavelength is  $10 \mu\text{m}$ . This yields a coating thickness of  $4.58 \mu\text{m}$ . This is the value used for the data in Fig. 3.

## 6. Wavelength-Dependent Phase Change and Tuning Range

Atherton, Reay, and Ring have accounted for the wavelength-dependent phase change by adding a fractional, wavelength-dependent-order correction,  $\epsilon\lambda$ .<sup>3</sup> This is the deviation (in radians) from the expected  $\pi$  radians phase change of the reflected wave.  $\epsilon\lambda/\pi$ , the fractional phase change, can be calculated from the striped mirror data using Eq. (8), where  $\ell$  is the cavity spacing derived from the uncoated free spectral range, and  $\lambda$  is the transmission peak wavelength.

$$\frac{\epsilon\lambda}{\pi} = \frac{2\ell - \lambda}{\lambda} \quad (8)$$

In Fig. 4,  $\epsilon\lambda/\pi$  is plotted versus the peak wavelength. Also shown is the phase change calculated from our thin-film program. They are in good agreement.

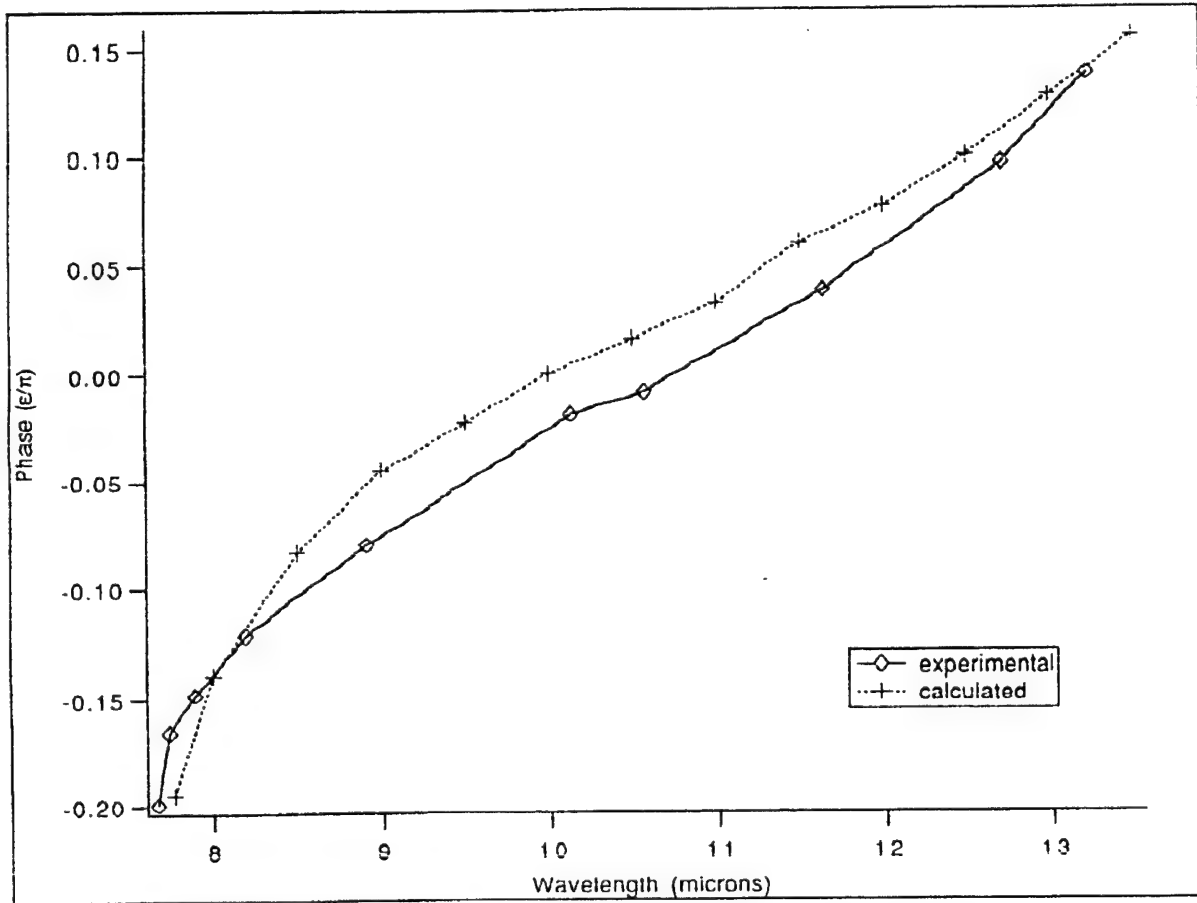


Figure 4. The fractional phase change as a function of peak wavelength.

The peak wavelength can now be calculated from the cavity spacing and the fractional phase change,

$$\lambda = \frac{2\ell}{n + \varepsilon_\lambda / \pi} . \quad (9)$$

Figure 5 shows a plot of the calculated peak wavelength versus cavity spacing for  $n = 0, 1, 2$ , and  $3$ . Figure 5 is useful for visualizing the FPI's tuning range. For instance, a first-order FPI tuned to a  $12\text{-}\mu\text{m}$  transmission peak would almost transmit  $7.3\text{ }\mu\text{m}$  radiation in second order. This is closer to our tuning range than the  $6\text{-}\mu\text{m}$  predicted by Eq. (2), but it can still be effectively blocked with an  $8\text{--}12\text{ }\mu\text{m}$  bandpass filter.

The zero-order transmission curve is of interest. For the coating design presented above, it occurs at a cavity spacing too small to be of interest. However, we have worked with another coating design that used 16 layers to produce a broad reflectance zone. The phase shifts for this design were quite large, even for wavelengths near the design wavelength. This caused the zero-order peaks to severely overlap the first-order peaks, and the tuning range was too small to be useful.

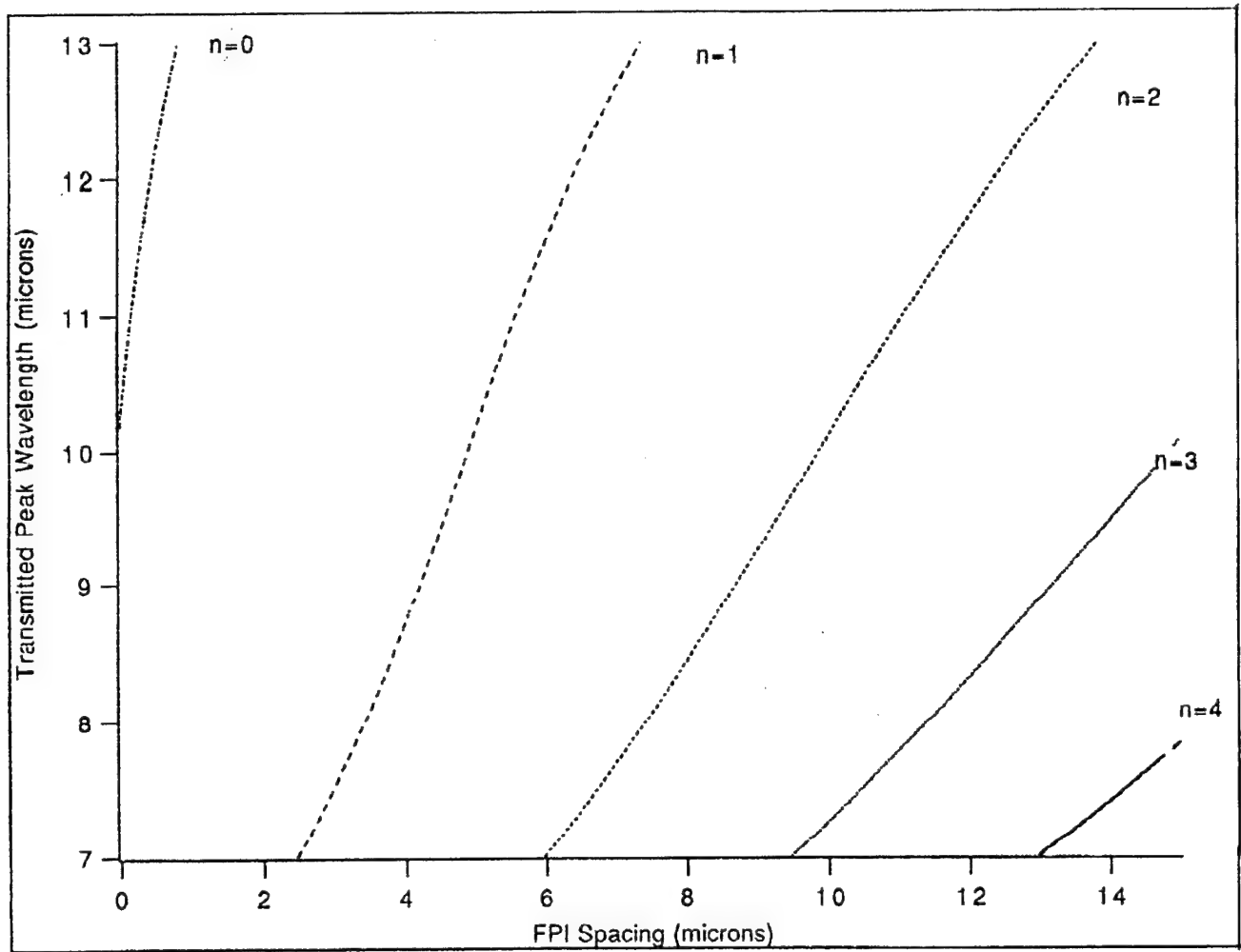


Figure 5. The peak wavelength versus cavity spacing for different orders.



## 7. Transmission Bandwidth

The wavelength-dependent phase change affects the transmission bandwidth. We expect the bandwidth to decrease as the reciprocal of the order [see Eq.(4)].

Atherton et al. have calculated the effect of the phase change on the bandwidth as given in Eq. (10)

$$\frac{\Delta\lambda(\%) }{\lambda} = \frac{1}{N_R \left( N + \frac{\epsilon_\lambda}{\pi} + \frac{\lambda}{\pi} \frac{d\epsilon_\lambda}{d\lambda} \right)}, \quad (10)$$

where

$$\frac{1}{\pi} \frac{d\epsilon_\lambda}{d\lambda}$$

is the slope of the phase change versus wavelength plotted in Fig. 4, and  $N_R$  is the reflective finesse given in Eq. (3).<sup>3</sup>

The calculated bandwidth with the phase correction [Eq.(10)] and without the phase correction [Eq. (4)] are shown as a function of wavelength in Fig. 6. The effect of the phase correction is to reduce the bandwidth by about 1–2%, depending on wavelength. The bandwidth of the transmission peaks, measured in an FTIR, are also shown in Fig. 6. They are in good agreement with the widths calculated from Eq. (10) with some differences at the beginning and end of the tuning range. The measured bandwidths are probably too large at these points because the transmission does not return to the baseline. This causes the transmission passband to change shape and distort the bandwidth measurement.

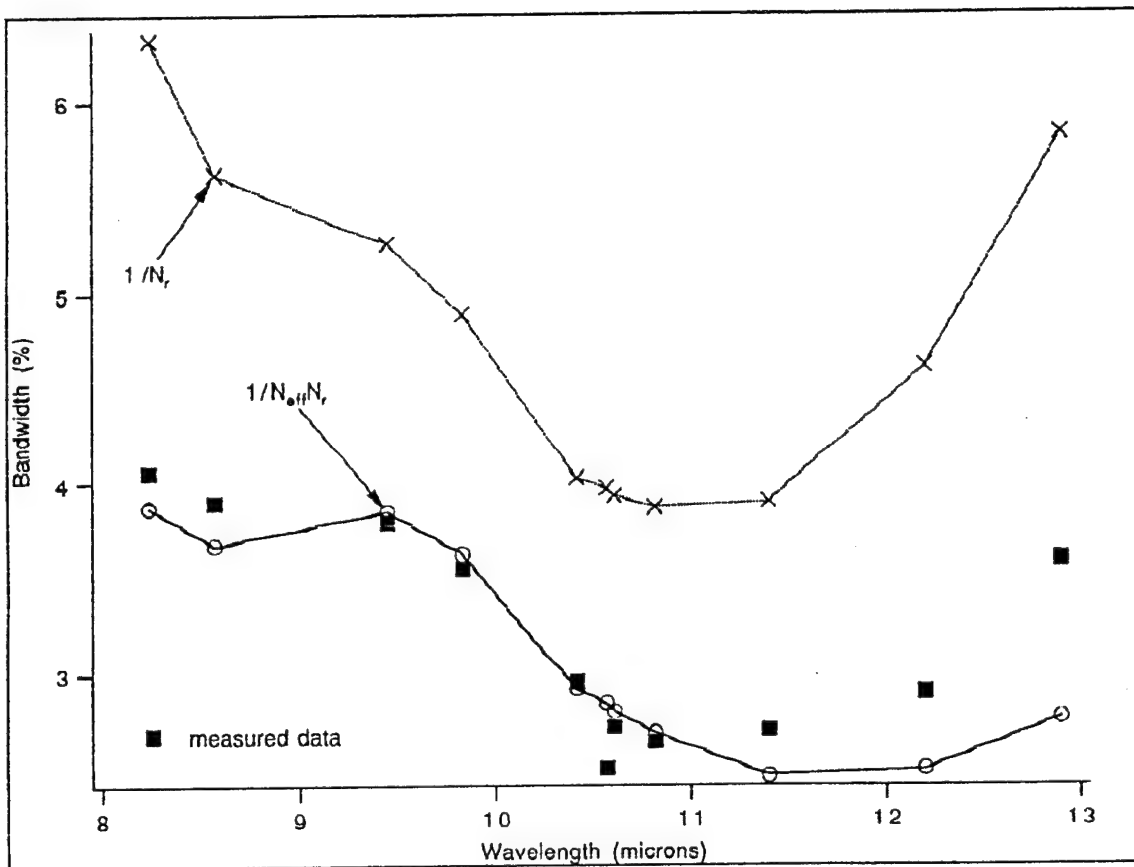


Figure 6. The transmission bandwidth as a function of wavelength. The (x) points are calculated based solely on reflectance (Eq. 3). The (O) points are calculated based on the fractional order model (Eq. 10). The (■) points are the measured bandwidths.

## 8. Wavelength Stability

The transmission peak was observed to drift between transmission measurements in the FTIR. The peak wavelength sometimes drifted a few percent (about one transmission peak width) overnight and infrequently over periods as short as several hours. This was probably due to room-temperature changes affecting the FPI cavity spacing.

The effect of temperature changes on the FPI can be calculated from the thermal expansion coefficient of the FPI and the change in transmitted peak wavelength with cavity spacing ( $d\lambda/d\ell$ ). The cavity length of the TL-38IR changes 51 nm/C°. The slope of Fig. 3,  $d\lambda/d\ell$ , at 10  $\mu\text{m}$  is 1.3. Therefore, the transmitted peak wavelength changes 0.066  $\mu\text{m}$  per C°. At 10  $\mu\text{m}$ , the full-bandwidth at half-height is 0.32  $\mu\text{m}$ . Therefore, a temperature change of 2.3°C is sufficient to shift the peak wavelength one-half width, which reduces the transmission at the original wavelength by one-half.

The wavelength stability due to room-temperature fluctuation was significantly improved by a foam rubber jacket around the FPI body. For outdoor use (in a field-portable spectrometer), a thin-film heater is being designed to compensate for the larger thermal variations.

## 9. Scanning and Dithering Capability

The first-order FPI was operated in a continuous-scan mode in order to record emission spectra in the 8.2–12.8  $\mu\text{m}$  region. A Burleigh RC-44 was used to generate a 0–1000 V sawtooth waveform. An  $f/1.5$  ZnSe lens immediately behind the FPI focused the transmitted radiation on a 1-mm<sup>2</sup> HgCdTe infrared detector. The source was either a 900°K blackbody fitted with one of several possible narrowband infrared filters, or a line-tunable waveguide CO<sub>2</sub> laser. A series of four filters in the 8.2–12.8  $\mu\text{m}$  region was used to calibrate the transmitted peak wavelength with sawtooth voltage.

The voltage-to-wavelength linearity was good up to 20 Hz scan rates. At faster rates, the FPI was unable to scan the full 8.2–12.8  $\mu\text{m}$  region. The reduced scan was due to the dampening effects of air on the mirror scanning motion. An FPI was installed in a vacuum container, and scan rates of 100 Hz were observed.

The transmission bandwidth, while scanning, was measured with the CO<sub>2</sub> laser at 10.3  $\mu\text{m}$ . The bandwidth was 3.2%, in good agreement with the bandwidth measured by the FTIR in the nonscanning mode, as shown in Fig. 6. The bandwidth measurements using the laser source were significantly more accurate and convenient than those using the blackbody/filter source. Since the bandwidths of the filters (1–3%) were comparable to the bandwidths of the FPI, the FPI bandwidth would have to be deconvoluted from the measured data.

The filter can tune smaller spectral intervals (i.e., 1  $\mu\text{m}$ ) at significantly higher rates. This is useful in some infrared radiometric situations where a narrowband molecular emission/absorption feature rides on top of a broadband (quasi-blackbody) background emission. The drive electronics can be modified to alternately tune filter wavelength to overlap the molecular feature and then to sample the background emission adjacent to the molecular feature. This spectral dithering produces a square-wave-modulated signal whose amplitude is proportional to the molecular emission radiance. It is essentially a rapid background subtraction technique.

The maximum rate of spectrally dithering depends on the size of the spectral interval. In one application where the filter dithered between 9.7–10.6  $\mu\text{m}$ , the maximum rate was 100 Hz. For smaller spectral intervals, about 0.1  $\mu\text{m}$ , we have been able to use the natural frequency of the piezoelectric drivers and produce stable dithering at 1 kHz.

## 10. Three-Micron Region Operation

The FPI can also operate in the 3.2–3.7  $\mu\text{m}$  region. The multilayer dielectric coating has a high-reflectance zone at one-third the design wavelength. This can be seen in Fig. 1, where the reflectance is 0.89 at 3.5  $\mu\text{m}$ . Figure 1 also shows that the width of the reflective zone at 3.5  $\mu\text{m}$  is only one-half as wide as expected from the design calculation. This is probably due to the small deviations from the design thicknesses.

The transmission of the FPI in the 3- $\mu\text{m}$  region is shown in Fig. 7 at two different cavity spacings. As the FPI is scanned through the 8–13  $\mu\text{m}$  region,  $n = 2, 3$ , and 4 peaks scan through this region. It is possible to collect spectra simultaneously in both the long- and short-wave regions by using a “sandwich” InSb/HgCdTe detector. The InSb detector absorbs the 3- $\mu\text{m}$  band radiation and transmits wavelengths longer than 5.8  $\mu\text{m}$ , which are detected by the HgCdTe. In the dual-band system, a blocking filter of the 5.8–8.2  $\mu\text{m}$  region would be required.

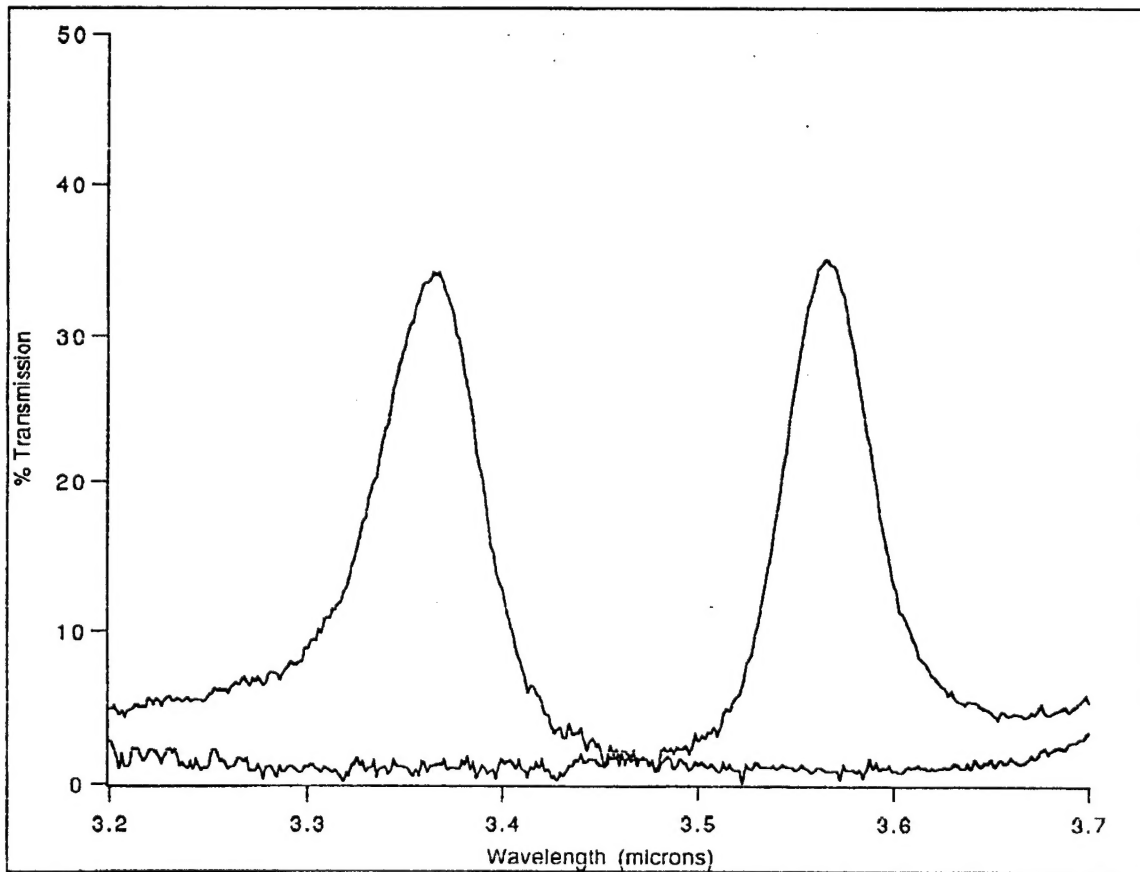


Figure 7. The FPI transmission in the 3- $\mu\text{m}$  region at two cavity spacings.

## 11. Summary

A scanning, first-order, Fabry-Perot infrared filter has been designed, constructed, and tested. In principle, a first-order FPI can scan from  $\lambda_{\max}$  to  $\lambda_{\max}/2$ . However, it is difficult to design partially transmitting mirror coatings that cover this large spectral range with uniform reflectivity. The coatings designed for our remote sensing requirements covered the 8.2–12.8  $\mu\text{m}$  range. The wavelength-dependent phase change from the thin-film multilayer dielectric coatings significantly affected the FPI wavelength tuning and transmitted bandwidth. However, these effects are well accounted for by using a model with a fractional, wavelength-dependent order correction. In addition, some loss of the FPI's transmission occurred in the 11–12.8  $\mu\text{m}$  region, probably due to weak absorption by  $\text{GeO}_2$  on the mirror coating. Because the filter is electronically tunable, it can provide several unique spectro-metric capabilities. It can scan the full 8.2–12.8  $\mu\text{m}$  range at 20 Hz, or it can dither between smaller spectral regions at rates up to 1 kHz, depending on the spectral interval.

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